PRE-CRASH SENSING COUNTERMEASURES AND BENEFITS

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ABSTRACT

This paper introduces a research plan by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation to be used for developing objective test procedures and estimating safety benefits of pre-crash sensing countermeasures. The main objective of pre-crash sensing applications is to sense a collision earlier than the current accelerometer-based approaches with anticipatory and more descriptive sensors, communicate this information to the vehicle and its occupant protection systems, and take appropriate actions to reduce the severity of crash injury. In addition, this paper provides preliminary results from a preparatory analysis to review state-of-the-art pre-crash sensing technology and applications, proposes a methodology to estimate their safety benefits, and defines relevant crash problems. The technology review is based on literature available in the public domain. The benefits estimation methodology is founded on the reduction of total harm by comparative assessment of crash injury with and without the assistance of pre-crash sensing systems. The crash problem is defined using the Crashworthiness Data System to identify relevant crashworthiness scenarios and their respective harm.

INTRODUCTION

Quicker crash sensing times and more robust information are required to upgrade vehicle safety involving deployment of occupant protection components. The main objective of pre-crash sensing applications is to sense a collision earlier than the current accelerometer-based approaches with anticipatory and more descriptive sensors, communicate this information to the vehicle and its occupant protection systems, and take appropriate actions to reduce the severity of crash injury. This type of crash countermeasure is aimed at reducing injuries once the crash is deemed unavoidable; as opposed to crash warning systems that help drivers avoid the crash.

Pre-crash sensing countermeasures fall under two categories. The first category encompasses reversible features that are activated just before a potential crash, but usually with the capability of being reset in case the crash does not occur. Examples include air bag pre-arming, non-pyrotechnic seat belt pre-tensioning, bumper extension or lowering, and emergency brake assist. The second category consists of non-reversible features that are initiated just before a crash, but usually with the drawback of not being re-settable, such as pyrotechnic seat belt pretensioning. System reliability is paramount for pre-crash sensing countermeasures, as is fast decision-making time, given the short time available to deploy such countermeasures. The potential benefits of pre-crash sensing applications span a number of vehicle-to-vehicle and vehicle-to-obstacle crash types.

This paper introduces a research plan by the NHTSA to be used for developing objective test procedures and projecting safety benefits for pre-crash sensing occupant protection technologies. NHTSA's goal is to use pre-crash sensing technology to automatically mitigate occupant injury severity once a crash has been determined inevitable. Preparatory analyses are currently underway to assess the state-of-the-art technology of pre-crash sensing countermeasures, define relevant crash problems, and devise a methodology to estimate their potential safety benefits.

The assessment of pre-crash countermeasure technologies is based on a literature review of widely available information from technical conferences and manufacturer's product development publications, both online and in print. A preliminary methodology is proposed to estimate the safety benefits of pre-crash countermeasures, which correlates pre-crash scenarios of vehicle movements and driver actions prior to the crash to crashworthiness scenarios based on vehicle damage area, vehicle type, driver type, air bag deployment, seat belt use, and driver seat track position. This methodology estimates total harm reduction by comparing crash injury severity between non-equipped vehicles and vehicles equipped with pre-crash sensing countermeasures. Relevant crash problems are defined using NHTSA's Crashworthiness Data System (CDS) crash databases from 1999 through 2003. This paper describes the CDS variables that were selected to identify the crashworthiness scenarios.

Next, this paper introduces NHTSA's research plan to address pre-crash sensing countermeasures. Preliminary results from a technology review of current pre-crash sensing systems follow. This paper then presents a methodology that estimates potential safety benefits of these countermeasures including the introduction of the term "harm units" for crashworthiness scenarios. This is followed by preliminary results from CDS crash analysis. Finally, this paper concludes with a discussion of preliminary analysis results and future research steps.

RESEARCH PLAN

The primary goal of NHTSA's research plan is to develop objective test procedures and estimate safety benefits for the most promising pre-crash sensing occupant protection technologies. The approach consists of the following steps:

- Define relevant crash problems.
- Determine performance specifications of pre-crash sensing countermeasures addressing the crash problems.
- Estimate preliminary safety benefits of potential countermeasures.
- Select safety-effective countermeasures for advanced development.
- Develop objective test procedures for selected countermeasures.
- Estimate fleet benefits.

The program plan proposed here allows for the motor vehicle industry to be involved from the beginning of the research. This early involvement aids in the research and development of pre-crash sensing systems while formulating objective test procedures to validate these systems.

The potential benefits of pre-crash sensing applications span a number of vehicle-to-vehicle and vehicle-to-obstacle crash types. The main safety objective of these systems is to minimize head and chest decelerations, upper neck forces and moments, and chest deflection. It should be noted, however, that research is needed to translate earlier deployment of occupant protection systems into significant improvements in injury mitigation. Studies are required to correlate the improvement in time-to-deploy and occupant protection for specific crash types, vehicle structures, and occupant characteristics. Such research must be founded on a better understanding of the crash problem and resulting injuries, countermeasure functional requirements, and capability of potential system technologies.

NHTSA is currently managing a cooperative research agreement with four consortia of automakers, known as the Crash Avoidance Metrics Partnership (CAMP), funded through the Federal Highway Administration (FHWA) Intelligent Transportation Systems (ITS) Program (#DTFH61-01-X-00014). This agreement is funded 65% by the U.S. government and 35% by the auto industry. This agreement includes collaborative work on performance metrics and objective tests for forward crash warning, performance requirements for enhanced digital maps for safety, performance requirements for vehicle safety communications, and identifying and analyzing driver workload metrics. The nature of this cooperative research provides a paradigm for the type of dialogue sought for pre-crash system development.

NHTSA's research path for pre-crash sensing countermeasures will involve the development of the necessary scientific basis in terms of test procedures through the CAMP cooperative agreement, with emphasis on reaching industry consensus on the test conditions and procedures for objectively evaluating pre-crash sensing systems. Figure 1 shows a proposed Gantt chart of this research plan that was initiated in 2004 with preparatory analyses to review technology and estimate preliminary safety benefits. A 3-year cooperative project between NHTSA and the automakers will develop objective test procedures, based on the results of the preparatory analyses. A parallel analytical effort will be undertaken to develop analytical results in support of NHTSA's inputs to the cooperative research as it proceeds. At the end of this research program, an understanding of the technology available and estimated safety benefits through objective testing will be available to NHTSA. This preparation will support NHTSA's adoption of a research path on pre-crash sensing technology.

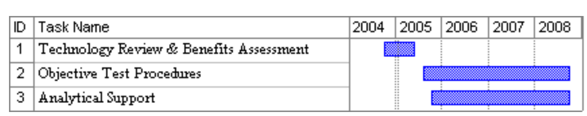

Figure 1 Major Tasks of NHTSA's Research Plan for Pre-Crash Sensing Countermeasures

TECHNOLOGY REVIEW

The technology review of pre-crash sensing countermeasures covered systems that are in any of the following developmental stages: concept, test-bed, prototype, or in production. This literature review was based on published information collected from technical conference proceedings, manufacturer's product or development Internet websites, and several other sources [1-13]. Preliminary results from the technology review are presented below, including a summary of R&D efforts among international manufacturers and research organizations. Moreover, the technology review describes the applications of pre-crash sensing technologies, their components, functionalities, available test results, and reported system effectiveness. In addition, the technology review helped to identify relevant crash scenarios for the crash problem definition, and to obtain technical data for modeling, such as pre-tensioning belt forces.

Worldwide R&D

The applications of pre-crash sensing technologies are classified into the following four groups:

- Seat belt pre-tensioning
- Emergency brake assist
- Seat adjustment
- Pedestrian protection

Table 1 summarizes international efforts in these applications by automakers and first tier suppliers. It should be mentioned that this tabular list was based on a limited literature review thus it may not be all-inclusive and might include redundant information between automakers and suppliers. While some applications have received greater attention (e.g., seat belt pre-tensioning), other applications have been studied less (e.g., seat adjustment). The following discusses details of the individual applications found so far.

Applications

A pre-crash sensing system is generally composed of sensors, decision-making units, actuators, and driver interfaces. The sensors may include both remote sensors and in-vehicle sensors. Computers or electronic control units (ECU's) serve as the decision-making units. These units process the signals received from the sensors and determine if a crash is unavoidable. Once a crash is determined to be imminent, the actuators deploy the safety systems automatically or upon receiving a signal from the driver interface, such as a pressure pulse on the brake pedal. The specifications of individual systems according to the applications are described next.

Seat Belt Pre-Tensioning and Emergency Brake Assist

Figure 2 illustrates the configuration of Toyota's Pre-Crash Safety (PCS) system with seat belt pre-tensioning and emergency brake assist applications

Table 1 Preliminary Summary of Worldwide R&D in Pre-Crash Sensing Applications

	Seat belt pre-tensioning [1-4, 7-8, 12-13]	Emergency brake assist [1-2, 5, 7, 13]	Seat adjustment [3-4, 12-13]	Pedestrian protection [6, 9, 10-11, 13]
Toyota, Japan	√	√		
DaimlerChrysler AG, Germany	√		√	
Ford, USA		√		
TRL Ltd., UK	√		√	√
Honda, Japan	√	√		
Nissan, Japan	√			√
BMW AG, Germany	√		√	
Autoliv, Sweden				√
Continental Teves	√	√	√	√

[1-2]. The system utilizes millimeter-wave radar as its remote sensor to detect obstacles and oncoming vehicle conditions. The PCS' ECU is shared with the adaptive cruise control (ACC) unit. The remote sensor signals, combined with vehicle sensor signals indicating vehicle yaw rates and steering angles, are sent to the pre-crash seat belt (PSB) and pre-crash brake assist (PBA) ECU's. If the ECU's detect an imminent crash or emergency braking, an electric motor automatically pre-tensions the seat belts. Tension is removed from the seat belt once the threat has passed and the seat belt returns to its original state. The PBA ECU analyzes inputs from vehicle wheel speed sensors and a brake pedal sensor, and will not deploy the brake assist until the driver has already stepped on the brake pedal.

Honda's Collision Mitigation Brake System (CMS) and E-Pretensioner also apply both the brake assist and seat belt pre-tensioning technologies [7]. However, Honda's CMS does not require that the driver brake to activate the brake assist – it will activate automatically once the system determines a collision is imminent. Automatic braking, as well as seat belt retraction, intensifies as the driver fails to respond to system warnings.

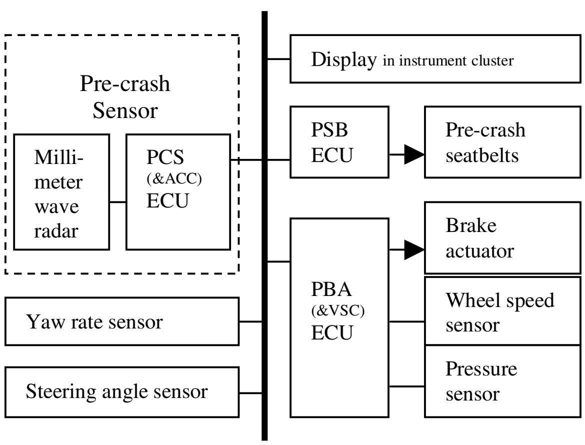

Figure 2. Configuration of Toyota's Pre-crash Safety System [1,2]

Seat Adjustment

DaimlerChrysler, BMW, and TRL studied a moving seat concept that involves moving an occupied seat from far forward to rearward positions just prior to a crash [3-4, 12]. While DaimlerChrysler and BMW provided only conceptual or descriptive information, TRL conducted a series of sled tests and described the results. These sled tests were conducted on 5th and 50th percentile dummies only, in conjunction with the use of pretensioners and variable air bag sizes/vent areas. A large occupant (such as a 95th percentile dummy) is assumed to sit already fairly rearward so moving the seat will not help as much as in the small and medium occupant cases. The tests did show additional protection provided by moving the seats rearward, in terms of reduced neck loads, chest accelerations and/or pelvic accelerations.

TRL did not describe any tests or results with out of position (OOP) occupants but was confident the moving seat concept can benefit this group of occupants as well. Presumably, the benefits will come from the potential of moving an OOP occupant out of the "danger zone".

DaimlerChrysler also explored the idea of seat back correction – a front passenger's seat back that is inclined far back can be moved into an upright position, in which the seat belts are expected to function more effectively.

Pedestrian Protection

This system uses sensors to detect an obstacle in front of a car. The sensors include frequency-modulated continuous-wave (FMCW) radar, laser, infrared imaging, contact sensor, accelerometers, etc. An algorithm is usually employed to discriminate a human from a non-human object. If a computer or an ECU determines that a collision with a pedestrian is impending, a number of technologies have been studied and can be deployed. These include a rear-lifting hood, air bags fitted to various parts of the vehicle front, and A-pillar air bag inflation [6, 9, 10-11, 13].

System Effectiveness

Evaluating system effectiveness is an important first step toward estimating the safety benefits introduced by pre-crash sensing countermeasures. Different types of technologies may contribute to different aspects of safety improvements. For example, the brake assist can reduce impact velocities; seat belt pre-tensioning can reduce occupant forward displacements and chest decelerations; pedestrian protection is aimed at reducing head impact velocities, head injuries, chest decelerations and lower extremity injuries; and moving seats can reduce injuries sustained by small or OOP occupants.

Based on the information gained from reviewing pre-crash sensing countermeasure technologies, this paper will next discuss estimation of their safety benefits. Estimated effectiveness values of pre-crash sensing systems in reducing relative speed or severity of impact due to seat belt tensioning, seat position movement or other measures found from the technology review will be factored into the analysis of system benefits and ultimately harm reduction. Additionally, sensor robustness and false alarm rates impact system benefits, and factor into how often a system responds correctly to a crash situation or incorrectly to a non-crash condition.

BENEFITS ESTIMATION METHODOLOGY

Figure 3 illustrates a general approach to estimate the safety benefits of pre-crash sensing countermeasures based on a concept of harm unit measurements. For a particular pre-crash sensing technology, target pre-crash scenarios addressed by the countermeasure as well as related driver response are examined. For scenarios resulting in an impact, detailed crashworthiness scenarios are analyzed to calculate harm units. Crashworthiness scenarios are based on factors that influence the crash characteristics such as change of speed at impact (ΔV), seat belt use, air bag deployment, seat track position, etc. Detailed description of variables used to define the crashworthiness scenarios is discussed in the sample data section of this paper. The CDS crash database is the source for the identification and harm computation for the crashworthiness scenarios.

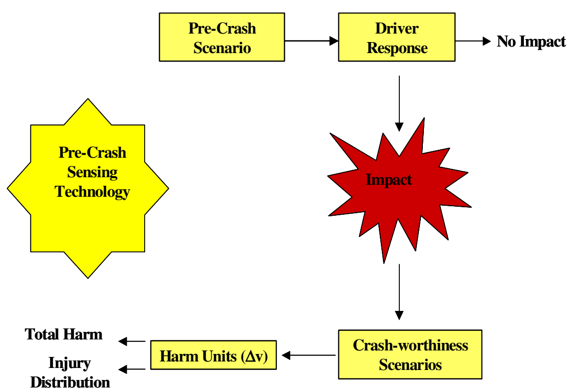

Figure 3. Benefits Estimation Approach

The CDS is a database that houses a collection of police reported crashes from the United States. Information is collected by twenty-four teams of crash researchers situated throughout the country, each investigating an appropriate probability sample of crashes involving passenger cars, light trucks, and vans, which were towed from the scene due to damage. The crash must involve a harmful event defined as resulting in either property damage or personal injury and the injury must be a result of the crash. Additionally, at least one vehicle involved in the crash must be in transport on a traffic-way. This excludes crashes that occur in private driveways and parking lots. Because the CDS only collects information for crashes where the vehicle is towed from the scene, damage must be significant enough to require assistance. It is difficult to speculate on the effect this may have on the comprehensiveness of the analysis of injury severity or crash magnitude, but it does affect the composition of the dataset explored by this preliminary crash analysis.

Harm Units Concept

Injury severity is the key measure to estimate the safety benefits of pre-crash sensing countermeasures. Equation (**1**) presents the calculation of harm units, which provides a cost (direct economic cost or functional years lost) for a particular combination of pre-crash scenario and crashworthiness scenario based on the distribution of injury severity. An example of this formula's application is given in the sample data section. Injury severity is measured on the Maximum Abbreviated Injury Scale (MAIS), whose values are shown in Table 2. Also shown in Table 2 are the direct economic costs, $w(i)$, associated with a particular MAIS level based on 2000 U.S. dollar amount [14]. The values of $I(i)$ are found from the CDS database query for injuries sustained by the driver (vehicle occupants). The parameter N_o represents the total number of drivers (occupants) involved. At this level of preliminary crash analysis and benefits estimation, only the driver injury was examined to keep cost comparisons between crashes of different pre-crash and crashworthiness scenarios the same regardless of varying factors such as the number of occupants.

$$\frac{\sum_{i=0}^{6} w(i) \times I(i)}{N_o} \qquad (1)$$

Once harm units are known for a particular combination of scenarios, the next step is to determine how much injury reduction, therefore harm reduction, results from the implementation of a pre-crash sensing system. Harm reduction, H_R, is calculated by subtracting total harm *with* the system, H_w, from total harm *without* the system, H_{wo}, as shown in Equation (**2**):

$$H_R = H_{wo} - H_w \qquad (2)$$

Table 2. MAIS Injury Description and Cost (Based on 2000 $ Amount)

MAIS	Cost
Uninjured	$ 1,962
Minor	$ 10,562
Moderate	$ 66,820
Serious	$ 186,097
Severe	$ 348,133
Critical	$ 1,096,161
Fatal	$ 977,208

Note: The costs shown in Table 2 reflect the dollar amount of economic costs. These include lost

productivity, medical costs, legal and court costs, emergency service costs, insurance administration costs, travel delay, property damage, and workplace losses.

The calculation of total harm *without* the system can be achieved with data from the CDS. On the other hand, calculating harm with a pre-crash sensing system will be based on information found in either the technology review or vehicle crash modeling in the first stages of benefits analyses, or through real-world testing in later stages. Modeling can be used to investigate how affecting seat position, movement, vehicle speed, or other factors prior to a crash may influence injury severity experienced by the driver. For example, a pre-crash brake system may identify that the host vehicle is rapidly approaching an object and a collision is imminent. If the system responded by applying the brakes to reduce speed, thus lessening ΔV, the injury severity of the driver would decrease. By reducing driver injury severity for any collision sensed by the pre-crash brake system, the distribution of injury severity levels should shift towards less severe injuries, decreasing overall harm.

Safety Benefits Calculation

$$H = N \sum_n C_n \times \sum_m R_m(C_n) \times \sum_i S_i(C_n, R_m) \times \sum_j P(\Delta V_j | S_i) \times \overline{H}(\Delta V_j | S_i) \quad \textbf{(3)}$$

N = Number of drivers involved in the crash
C = Relative frequency of certain crash type
R = Relative frequency of certain driver attempted avoidance maneuver
S = Relative frequency of certain scenario
P = Probability of certain scenario for ΔV_i given S_i
$\overline{H}$ = Harm unit, average harm per driver for ΔV_i given S_i
= Parameters to change with pre-crash technology

Equation (**3**) breaks down the computation of total harm by a number of components that might be affected by various pre-crash sensing applications. The calculation of safety benefits in terms of total harm reduction is then based on computing H_{wo} and H_w according to Equation (**3**). The computation of H_{wo} requires two separate queries into the CDS. The first query examines pre-crash scenarios and driver response prior to the crash. The second query explores crash conditions such as location of damage, driver characteristics, restraint systems, and ΔV.

The first three factors of Equation (**3**) depend on information pertaining to pre-crash data, whereas the remaining factors rely on crashworthiness data. The harm units are represented by $\overline{H}(\Delta v_i \mid S_i)$. For the above example of a pre-crash brake system, only the ΔV factor is affected by the system, resulting in a different $P(\Delta v_i|S_i)$ *with* the system than *without*. This will affect the last summation of Equation (**3**). The third factor connects crashworthiness scenarios, S_i, with pre-crash scenarios C_n. For a pre-crash brake system, C_n values might include stationary objects or vehicles, and vehicles accelerating, decelerating, or traveling at constant speed. The equation specifies pre-crash scenarios by vehicle movements prior to the crash because some systems have sensing limitations that affect the number of scenarios they address. Also included is driver response to the pre-crash scenario because this will also limit the number of crashes a system may address. As discussed previously in the technology review, some pre-crash brake systems respond to potential collision situations automatically; others require driver braking before activation.

FRONTAL DAMAGE SCENARIO DESCRIPTION AND SAMPLE DATA

The CDS database contains crash files of all types and severities [15]. Some crashes result in multiple impact events. The preliminary crash analysis concentrated on crashes with frontal damage only as the first event, and filtered out crashes with multiple impact events since other factors might have influenced the injury severity sustained by the driver. In addition, the crash vehicle population was divided into four categories: automobile, light truck, sport utility vehicle (SUV), and van. This split was necessary due to different body structures and crash performance characteristics. Table 3 lists CDS variables that the preliminary crash analysis addressed to describe frontal damage crashes.

Table 3. CDS Variables Used in Frontal Damage Analysis

Pre-Crash Scenario Variables
Accident type
Attempted avoidance maneuver
Crashworthiness Scenario Variables
Δ V
Offset
Air bag deployment
Seat belt use
Seat track position
Driver weight

Pre-crash scenarios of interest can be identified from the Accident Type and the five pre-crash variables in the CDS. However, this preliminary crash analysis focused on the Accident Type variable and the Attempted Avoidance Maneuver pre-crash variable. The applicability of pre-crash sensing countermeasures depends on the dynamic characteristics of pre-crash scenarios. Most rear-end collisions incur damage to the front of the striking vehicle; however, some striking vehicles may end up with a damage area other than the front part of the vehicle due to driver evasive maneuver. For example, a driver may try to avoid hitting a vehicle stopped at an intersection by braking and steering. This maneuver may result in the vehicle skidding sideways and striking the vehicle at the intersection with the side of their vehicle. Other potential maneuvers include braking only, steering only, and no response.

Crashworthiness scenarios are built with variables that have bearing on crash characteristics and therefore driver injury severity. The most important factor is ΔV, which identifies the change in velocity experienced by the vehicle and its driver. Crash offset measures the location of the crash relative to the center of the vehicle, determining over what area the crash energy is absorbed. It is calculated taking into account several CDS factors including direction of force, general area of vehicle damage, vehicle deformation location, and horizontal location of vehicle damage. By combining all these factors into the offset variable, many details about crash specifics were found through one variable. The CDS codes of air bag deployment and seat belt use were consolidated into either yes, no, or unknown conditions. To operate as intended, pre-crash countermeasures utilizing seat belt pretensioning require seat belt use information. Driver seat track position was also considered. This variable measures longitudinal location, which may change if a pre-crash sensing application moves the seat back when an impending crash is detected. Finally, driver weight was selected to represent the driver factor, which cannot be influenced by any system but it may affect how a system modulates seat belt pre-tension or seat track location.

Next, sample results from the preliminary crash analysis based on the 1999-2003 CDS are presented to illustrate the definition of crashworthiness scenarios and the computation of concomitant harm units. Table 4 provides crash statistics in terms of the number of drivers and relative frequency, in a descending order, for crashworthiness scenarios of automobiles involved in frontal damage crashes. In addition to variations of crash offset, seat track position, and driver weight, these scenarios include air bag deployed and seat belt used conditions. Combinations of crash offset, driver seat track position, and driver weight amount to a total of 60 potential crashworthiness scenarios, S_i in Equation **(3)**. Table 4 only lists the scenarios with individual relative frequency of 1% and higher, comprising approximately 91% of total drivers for these scenario combinations. "Full Frontal" crash offset indicates minimal or no frontal offset, and crashes not fitting any other offset category are classified as "Frontal Other". Light drivers weigh less than 150 pounds, medium-weight drivers are greater than or equal to 150 but less than 190 pounds, and heavy driver weigh 190 pounds or more.

Table 4. Crashworthiness Scenario Frequency for Automobile, Frontal Damage, Belted Driver, and Air bag Deployed Crashes (Based on 1999-2003 CDS)

Crash Offset	Seat Track Position	Driver Weight	# of Vehicles	Relative Frequency
Right	Middle	Medium	42,090	7%
Left	Middle-Rear	Light	35,501	6%
Left	Forward	Light	33,938	6%
Full Frontal	Rear	Light	32,574	6%
Right	Rear	Medium	29,159	5%
Full Frontal	Rear	Heavy	29,134	5%
Left	Rear	Heavy	24,990	4%
Right	Forward	Light	19,113	3%
Full Frontal	Middle	Light	19,098	3%
Right	Middle	Light	18,082	3%
Front Other	Middle-Rear	Medium	17,808	3%
Right	Middle-Rear	Medium	17,666	3%
Left	Rear	Medium	17,457	3%
Full Frontal	Middle	Medium	16,812	3%
Full Frontal	Rear	Medium	16,487	3%
Left	Forward	Medium	16,247	3%
Left	Middle	Medium	16,141	3%
Right	Forward	Medium	15,581	3%
Left	Middle	Heavy	14,659	2%
Left	Middle	Light	14,503	2%
Right	Rear	Heavy	14,459	2%
Left	Middle-Rear	Medium	12,499	2%
Right	Rear	Light	11,393	2%
Full Frontal	Middle-Rear	Light	10,747	2%
Left	Rear	Light	10,369	2%
Full Frontal	Middle-Rear	Heavy	9,495	2%
Full Frontal	Forward	Medium	8,670	1%
Full Frontal	Middle-Rear	Medium	7,624	1%
TOTAL			532,297	91%

Further statistics on the most frequent scenario in Table 4 are provided to demonstrate harm calculations. Table 5 lists a breakdown of crash relative frequency for this scenario by ΔV, including both recalculated and estimated ΔV values from the CDS. These values are represented by the parameter *P* in Equation **(3)**.

Average harm unit value, found using Equation **(1)**, requires a distribution of crash injury severity from the MAIS, number of drivers, N_o, and cost of the injury *w(i)* from Table 2. Using the two most frequent known ΔV values as an example, this paper now demonstrates how harm units are calculated.

Table 5. ΔV Distribution for Offset Right, Middle Seat Track, and Middle Weight Scenario

Δ V (kmph)	% of Total
Δ V<10	0%
10≤Δ V<25	41%
25≤Δ V<40	14%
40≤Δ V<55	2%
55≤Δ V	0%
Minor	0%
Moderate	1%
Severe	0%
Unknown	43%
TOTAL	100%

Table 6 shows the number of drivers by MAIS severity for the selected scenario and two ΔV ranges. Injury levels are likely on the lower end of the scale due to relatively low ΔV values, generally lower harm crash type and crashworthiness conditions of air bag deployed and seat belt used. The cost of crashes is calculated in the last two columns by multiplying harm cost with the number of drivers for each MAIS severity. To arrive at average harm per driver, total cost of crashes for each column is divided by the total number of drivers for that ΔV. This results in an average cost per driver for a specific scenario-ΔV combination, which completes the last term of Equation (**3**). These values illustrate that if a pre-crash sensing countermeasure reduced ΔV for a forward collision type, shifting the distribution of ΔV's to lower value ranges, the system would decrease average harm per driver. Thus, according to Equation (**2**), this would translate to a harm reduction due to system use.

Table 6. Injury Severity and Average Cost for Selected ΔV for Offset Right, Middle Seat Track, and Middle Weight Scenario

MAIS	Number of Crashes		Harm Cost	Cost of Crashes	
	$10 \leq \Delta V < 25$	$25 \leq \Delta V < 40$		$10 \leq \Delta V < 25$	$25 \leq \Delta V < 40$
Uninjured	406	1,245	$ 1,962	$ 796,380	$ 2,442,872
Minor	16,563	4,409	$ 10,562	$ 174,940,687	$ 46,567,668
Moderate	15	321	$ 66,820	$ 1,009,984	$ 21,442,204
Serious	-	36	$ 186,097	$ -	$ 6,759,974
Severe	-	-	$ 348,133	$ -	$ -
Critical	-	-	$ 1,096,161	$ -	$ -
Fatal	-	-	$ 977,208	$ -	$ -
TOTAL	16,984	6,011		$ 176,747,051	$ 77,212,718
		Average Harm per Driver		$ 10,407	$ 12,845

DISCUSSION

The following discusses issues related to a better understanding of the crash problems and crashworthiness scenarios that pre-crash sensing countermeasures address, and the use of computer modeling to determine system effectiveness in reducing the severity of crash injury.

Crash Analysis

As demonstrated by preliminary crash data in this paper, there are several limitations of the CDS database. After aggregating 5 years of data, several injury severity cells were empty for the most common crashworthiness scenarios. There are two potential solutions to this weakness. First, more years of CDS data could be used to increase the sample size; however, complexities might arise in data query if CDS variables and codes have changed over the years. CDS databases could be used dating back to 1992 when pre-crash variables were introduced into the CDS. A second approach to dealing with the lack of adequate cases in the CDS is to not have such finely defined crashworthiness scenarios. For example, a rear-end pre-crash sensing countermeasure may reduce ΔV and therefore injury severity and not have any interaction and effect on seat belt use, seat position etc. With less crashworthiness factors, each scenario would be represented by more cases, but this assumption will not work for countermeasures that affect multiple factors either directly or indirectly.

A second weakness of the CDS is the relatively high frequency of variables coded as "unknown". As seen in Table 5, certain scenarios resulted in high-unknown values, although typically unknown values are much lower. One way to compensate is to redistribute them proportionally based on relative frequency among known values.

Modeling

The harm units without pre-crash sensing countermeasures can be calculated from the injury probability data obtained from analyses of the CDS database. In some cases, database analyses can also yield an estimation of the harm units with the countermeasures. For example, such analyses readily yield the system effectiveness of emergency brake assists (in terms of reduced ΔV), or that of seat tracks positioned more rearward. In other cases, however, pre-crash sensing countermeasures need to be implemented in physical testing or mathematical simulations to give a direct evaluation of the system effectiveness. Between these two methods, mathematical modeling is often more cost-effective.

With a modeling approach, first the analysis methods will be determined and vehicle-occupant models will be identified. While either finite element or rigid body dynamics (RBD) models can be utilized, the large size of prospective simulations will most likely lead to RBD as the method of choice owing to its much lesser demand on computational resources. There is a family of occupant models available, but some vehicle models in RBD, especially those with major load bearing structures, may not actually exist. An occupant compartment model can be used instead, but a crash pulse to the occupant is needed in such cases.

The inputs to a model will be generated based on the information from the CDS database analyses. A crash pulse can be reconstructed from such information as crash type, general area of damage, ΔV, direction of force and offset. However, it should be noted that the available crash information is limited and a reconstructed crash pulse will not be unique. Driver weight data can be used to determine the type of occupant models. Pre-crash sensing countermeasures are realized in the simulations via proper setups of air bag deployment, seat belt forces, etc.

To satisfy the common requirement of validating a model (or models) before applying it in application simulations and gaining insights from its outputs, it is proposed that for each simulation with one type of countermeasure applied, a corresponding case without the countermeasure is also simulated and the outputs compared with the results from the database analyses. This practice can help to gain a level of confidence in the modeling approach. However, it can also double the total number of simulations to be conducted.

The outputs from the simulations include injury criteria in different body regions. Injury risk functions, available for head, neck, thorax and lower extremities, can translate these injury criteria into injury probabilities that are comparable to CDS MAIS data. However, simulated injury probabilities are available in four of the above mentioned body regions, and it remains to be determined whether the injury probabilities in one selected body region, or a certain combination of the four, are to be used in the harm unit calculations.

CONCLUSIONS

This paper introduced a research plan to be used by NHTSA to understand the preliminary safety benefits of pre-crash sensing countermeasures and develop objective test procedures for most promising systems. As part of this research effort, preliminary analyses have been conducted to review the technology and applications of current pre-crash sensing systems, define their crash problems, and devise a methodology to estimate their safety benefits. Preliminary results of technology review, high-level benefits estimation methodology, and crash analysis were presented.

The technology review identified 4 major pre-crash sensing countermeasure technologies: seat belt pretensioning, emergency brake assist, seat adjustment and pedestrian protection. A preliminary estimation of the benefits from an emergency brake assist countermeasure was conducted using the 1999-2003 CDS. For a certain combination of crashworthiness variables, reducing ΔV from the [25, 40) range to the [10,25) range resulted in an average harm reduction per driver of $2,438 (from $12,845 to $10,407).

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